Interaction of the pseudoscalar glueball with (pseudo)scalar mesons and nucleons*

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We study the interactions of the pseudoscalar glueball with scalar and pseudoscalar quark-antiquark meson fields and with the nucleon and its chiral partner. In both cases we introduce the corresponding chiral Lagrangian and discuss its properties. We calculate the mesonic and baryonic decays of a pseudoscalar glueball with mass of about 2.6 GeV as predicted by Lattice simulations.

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1. Introduction

The investigation of the properties of bound state of gluons, the so-called glueballs, represents an important step toward the understanding of the nonperturbative aspects of Quantum Chromodynamics (QCD). The search for glueballs is also relevant in the framework of hadron phenomenology, as they might explain the nature of some enigmatic mesonic resonances (see Ref. [1] and refs. therein).

Lattice QCD is a well-established non-perturbative approach to solve QCD: within this context the glueball spectrum has been obtained [2], where the lightest glueball has $J^{PC} = 0^{++}$ quantum numbers and a mass of about 1.6 GeV. This energy region has been studied in a variety of effective approaches, e.g. Refs. [3, 4]. The second lightest glueball has been predicted to be a tensor ($J^{PC} = 2^{++}$), see also Ref. [5] for a related phenomenological discussion. The third lightest state is a pseudoscalar glueball ($J^{PC} = 0^{-+}$) with a mass of about 2.6 GeV. This value represents the starting point of our

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investigation of the properties of the pseudoscalar glueball [6] (for scenarios with a lower mass see Ref. [7] and refs. therein).

Namely, we study the interactions of the pseudoscalar glueball, denoted as $\tilde{G}$, to scalar and pseudoscalar mesons: we discuss the symmetry properties of the effective Lagrangian introduced in Ref. [6] and we present the results for the branching ratios for the two-body decays (one scalar and one pseudoscalar state) and for the three-body decays (three pseudoscalar states). Then, we comment on a particular interference problem, only mentioned in Ref. [6], which emerges from the subsequent decay of a scalar meson of the two-body decay into two pseudoscalar states: both decay mechanism end up in the same final states and therefore care is needed. Next, we describe (to our knowledge for the first time) the interaction of $\tilde{G}$ with baryons: we introduce the chiral effective Lagrangian which couples $\tilde{G}$ to the nucleon field and its chiral partner. This Lagrangian describes also the proton-antiproton conversion process $\bar{p}p \to \tilde{G}$, which can take place in the planned PANDA experiment at the upcoming FAIR facility in Darmstadt [8], in which the (center of mass) energy range above 2.5 GeV will be investigated.

2. Interaction with (pseudo)scalar mesons

The effective Lagrangian which couples the pseudoscalar glueball field, $\tilde{G}$ with quantum numbers $J^{PC} = 0^{-+}$ to scalar and pseudoscalar mesons read [6, 9]

$$\mathcal{L}^{int}_{\tilde{G}\text{-mesons}} = ic_{\tilde{G}\Phi}\tilde{G}\left(\det\Phi - \det\Phi^{\dagger}\right) \,, \tag{1}$$

where $c_{\tilde{G}\phi}$ is the (unknown) coupling constant. The scalar and pseudoscalar mesons are organized in the multiplet Φ [10]:

$$\Phi = \frac{1}{\sqrt{2}}\begin{pmatrix} \frac{(\sigma_N + a_0^0) + i(\eta_N + \pi^0)}{\sqrt{2}} & a_0^+ + i\pi^+ & K_S^+ + iK^+ \\ a_0^- + i\pi^- & \frac{(\sigma_N - a_0^0) + i(\eta_N - \pi^0)}{\sqrt{2}} & K_S^0 + iK^0 \\ K_S^- + iK^- & \bar{K}_S^0 + i\bar{K}^0 & \sigma_S + i\eta_S \end{pmatrix} \tag{2}$$

which transforms as $\Phi \to U_L \Phi U_R^{\dagger}$ under chiral transformations of the group $U(3)_R \times U(3)_L$, whereas $U_{L(R)} = e^{-i\theta^a_{L(R)}t^a}$ is an element of $U(3)_{R(L)}$. The pseudoscalar glueball $\tilde{G}$ consists of gluons and is a chirally invariant object. It follows that the Lagrangian (1) is invariant under $SU(3)_R \times SU(3)_L$ transformations, but is not invariant under the axial $U_A(1)$ transformation, because:

$$\det\Phi \to \det U_A \Phi U_A = e^{-i\theta_A^0\sqrt{2N_f}}\det\Phi \neq \det\Phi \,.$$

We now turn to discrete symmetries. The parity transformation $\mathcal{P}$ of the multiplet Φ reads $\Phi(t,\vec{x}) \to \Phi^{\dagger}(t,-\vec{x})$ and that of the glueball reads $\tilde{G}(t,\vec{x}) \to -\tilde{G}(t,-\vec{x})$. It is then easy to verify that the Lagrangian (1) is parity invariant. Under charge conjugation $\mathcal{C}$ the transformations $\Phi \to \Phi^T$ and $\tilde{G} \to \tilde{G}$ hold, in virtue of which the Lagrangian (1) is also left invariant.

The assignment of the quark-antiquark fields in our work is as follows: (i) In the pseudoscalar sector the fields $\vec{\pi}$ and K represent the pions or the kaons, respectively. The bare fields $\eta_N \equiv \left|\bar{u}u + \bar{d}d\right\rangle/\sqrt{2}$ and $\eta_S \equiv |\bar{s}s\rangle$ are the non-strange and strange mixing contributions of the physical states η and η' . (ii) In the scalar sector we assign the field $\vec{a}_0$ to the physical isotriplet state $a_0(1450)$ and the scalar kaon fields K_S to the resonance $K_0^{\star}(1430)$. The fields $\sigma_N \equiv \left|\bar{u}u + \bar{d}d\right\rangle/\sqrt{2}$ and $\sigma_S \equiv |\bar{s}s\rangle$ correspond to the physical resonances $f_0(1370)$ and $f_0(1710)$. The small mixing of the bare fields σ_N and σ_S is neglected here [10].

To evaluate the decays of the pseudoscalar glueball $\tilde{G}$ we have to take into account that the spontaneous breaking of chiral symmetry takes place, which implies the shift of the scalar-isoscalar fields as $\sigma_N \to \sigma_N + \phi_N$ and $\sigma_S \to \sigma_S + \phi_S$, where ϕ_N and ϕ_S represent the chiral non-strange and strange condensates. In addition, due to the fact that also (axial-)vector mesons are present in the full Lagrangian [4, 10, 11], one has also to 'shift' the axial-vector fields and to redefine the renormalization constant of the pseudoscalar fields, $\vec{\pi} \to Z_\pi \vec{\pi}$, $K \to Z_K K$, $\eta_{N,S} \to Z_{\eta_{N,S}} \eta_{N,S}$, where the quantities Z_i are the wave function renormalization constants. The theoretical results for the two-body and three-body branching ratios of the pseudoscalar glueball $\tilde{G}$ as evaluated from Eq. (1) are summarized in Table I.a and I.b for the mass $M_{\tilde{G}} = 2.6$ GeV, see also Ref. [6]. Note, the ratios are independent on the unknown coupling $c_{\tilde{G}\Phi}$ and represent a prediction of our approach.

Quantity	Value
$\Gamma_{\tilde{G}\to KK\eta}/\Gamma_{\tilde{G}}^{tot}$	0.049
$\Gamma_{\tilde{G}\to KK\eta'}/\Gamma_{\tilde{G}}^{tot}$	0.019
$\Gamma_{\tilde{G}\to \eta\eta\eta}/\Gamma_{\tilde{G}}^{tot}$	0.016
$\Gamma_{\tilde{G}\to \eta\eta\eta'}/\Gamma_{\tilde{G}}^{tot}$	0.0017
$\Gamma_{\tilde{G}\to \eta\eta'\eta'}/\Gamma_{\tilde{G}}^{tot}$	0.00013
$\Gamma_{\tilde{G}\to KK\pi}/\Gamma_{\tilde{G}}^{tot}$	0.46
$\Gamma_{\tilde{G}\to \eta\pi\pi}/\Gamma_{\tilde{G}}^{tot}$	0.16
$\Gamma_{\tilde{G}\to \eta'\pi\pi}/\Gamma_{\tilde{G}}^{tot}$	0.094

Quantity	Value
$\Gamma_{\tilde{G}\to KK_S}/\Gamma_{\tilde{G}}^{tot}$	0.059
$\Gamma_{\tilde{G}\to a_0\pi}/\Gamma_{\tilde{G}}^{tot}$	0.083
$\Gamma_{\tilde{G}\to \eta\sigma_N}/\Gamma_{\tilde{G}}^{tot}$	0.028
$\Gamma_{\tilde{G}\to \eta\sigma_S}/\Gamma_{\tilde{G}}^{tot}$	0.012
$\Gamma_{\tilde{G}\to \eta'\sigma_N}/\Gamma_{\tilde{G}}^{tot}$	0.019

Table I.a (left): Branching ratios for the three-body decays $\tilde{G} \to PPP$.
Table I.b (right): Branching ratios for the two-body decays $\tilde{G} \to SP$.

An interesting and subtle issue is the following: the scalar states decay further into two pseudoscalar ones. For instance, $K_S \equiv K_0^*(1430)$ decays into $K\pi$. There are then two possible decay amplitudes for the process $\tilde{G} \to KK\pi$: one is the direct decay mechanism reported in Table I.a, the other is the decay chain $\tilde{G} \to KK_S \to KK\pi$. The immediate question is, if interference effects emerge which spoil the results presented in Table I.a and I.b. Namely, simply performing the sum of the direct three-body decay (Table I.a) and the corresponding two-body decay (table I.b) is not correct.

We now describe this point in more detail using the neutral channel $\tilde{G} \to K^0\bar{K}^0\pi$ as an illustrative case. To this end, we describe the coupling $K_S = K_0^*$ to $K\pi$ via the Lagrangian

$$\mathcal{L}_{K_S K\pi} = gK_0^*\bar{K}_0\pi^0 + \sqrt{2}gK_0^*K^-\pi^+ + h.c. \,. \tag{3}$$

The coupling constant $g = 2.73$ GeV is obtained by using the experimental value for the total decay width $\Gamma_{K_0^*} = 270$ MeV [12]. The full amplitude for the process $\tilde{G} \to K^0\bar{K}^0\pi^0$ results as the sum

$$\mathcal{M}^{\text{full}}_{\tilde{G}\to K^0\bar{K}^0\pi^0} = \mathcal{M}^{\text{direct}}_{\tilde{G}\to K^0\bar{K}^0\pi^0} + \mathcal{M}^{\text{via}K_S}_{\tilde{G}\to \bar{K}^0K_S^0 \cdot\to K^0\bar{K}^0\pi^0} + \mathcal{M}^{\text{via}\bar{K}_S}_{\tilde{G}\to K^0\bar{K}_S^0 \cdot\to K^0\bar{K}^0\pi^0} \tag{4}$$

Thus for the decay width we obtain

$$\begin{aligned}\Gamma^{\text{full}}_{\tilde{G}\to K^0\bar{K}^0\pi^0} = \Gamma^{\text{direct}}_{\tilde{G}\to K^0\bar{K}^0\pi^0} + \Gamma^{\text{via}K_S}_{\tilde{G}\to K^0K_S^0\to K^0\bar{K}^0\pi^0} + \\ \Gamma^{\text{via}\bar{K}_S}_{\tilde{G}\to K^0\bar{K}_S^0 \cdot\to K^0\bar{K}^0\pi^0} + \Gamma^{\text{mix}}_{\tilde{G}\to K^0\bar{K}^0\pi^0}\end{aligned} \tag{5}$$

where $\Gamma^{\text{mix}}_{\tilde{G}\to K^0\bar{K}^0\pi^0}$ is the sum of all interference terms. We can then investigate how large the mixing term Γ_{mix} is, and thus the error done in neglecting it. The explicit calculation for the $K^0\bar{K}^0\pi^0$ case gives a relative error of

$$\left| \frac{\Gamma^{\text{mix}}_{\tilde{G}\to K^0\bar{K}^0\pi^0}}{\Gamma^{\text{direct}}_{\tilde{G}\to K^0\bar{K}^0\pi^0} + \Gamma^{\text{via}K_S}_{\tilde{G}\to K^0K_S^0\to K^0\bar{K}^0\pi^0} + \Gamma^{\text{via}\bar{K}_S}_{\tilde{G}\to K^0\bar{K}_S^0 \cdot\to K^0\bar{K}^0\pi^0}} \right| \approx \begin{array}{c} 7.3\ \%\ (g>0) \\ 2.2\ \%\ (g<0) \end{array} \tag{6}$$

Present results from the model in Ref. [10] show that $g < 0$: the estimates presented in Ref. [6] can be regarded as upper limits. We thus conclude that the total error for the channel $\tilde{G} \to K^0\bar{K}^0\pi^0$ is not large and can be neglected at this stage. However, in future more detailed and precise theoretical predictions, these interference effects should also be taken into account.

3. Interaction with baryons

In the planned PANDA experiment at FAIR [8] antiprotons collide on a proton rich target. It is then also interesting to study how the pseudoscalar glueball interacts with the nucleon (and with its chiral partner). In the so-called mirror assignment [13, 14], one starts from two nucleon fields Ψ_1 and Ψ_2 which transform in under chiral transformations as follows:

$$\Psi_{1R(L)} \longrightarrow U_{R(L)}\Psi_{1R(L)}\ ,\ \Psi_{2R(L)} \longrightarrow U_{L(R)}\Psi_{2R(L)}\ . \tag{7}$$

In this way it is possible to write down a chirally invariant mass term of the type

$$\mathcal{L}_{m_0} = -m_0\left(\overline{\Psi}_2\gamma_5\Psi_1 - \overline{\Psi}_1\gamma_5\Psi_2\right). \tag{8}$$

(Eventually, the latter can be seen as a condensation of a tetraquark and/or a glueball field, details in Refs. [14]). The nucleon fields N and its chiral partner (associated to the resonance $N^*(1535)$) are obtained as

$$\Psi_1 = \frac{1}{\sqrt{2\cosh\delta}}\left(Ne^{\delta/2} + \gamma_5 N^* e^{-\delta/2}\right)\ , \tag{9}$$

$$\Psi_2 = \frac{1}{\sqrt{2\cosh\delta}}\left(\gamma_5 N e^{-\delta/2} - N^* e^{\delta/2}\right)\ , \tag{10}$$

where

$$\cosh\delta = \frac{m_N + m_{N^*}}{2m_0}\ . \tag{11}$$

The value $m_0 = 460 \pm 136$ MeV was obtained by a fit to vacuum properties [14].

We now write down a chirally invariant Lagrangian which describes the interaction of $\tilde{G}$ with the baryon field Ψ_1 and Ψ_2

$$\mathcal{L}^{int}_{\tilde{G}\text{-baryons}} = ic_{\tilde{G}\Psi}\tilde{G}\left(\overline{\Psi}_2\Psi_1 - \overline{\Psi}_1\Psi_2\right)\ . \tag{12}$$

Thus, the fusion of a proton and an antiproton is described by $\mathcal{L}^{int}_{\tilde{G}\text{-baryons}}$, showing that it is not chirally suppressed. Moreover, although the coupling constant $c_{\tilde{G}\Psi}$ cannot be determined, we can easily predict the ratio of the decay processes $\Gamma_{\tilde{G}\to\overline{N}N}$ and $\Gamma_{\tilde{G}\to\overline{N^*}N+h.c.}$,

$$\frac{\Gamma_{\tilde{G}\to\overline{N}N}}{\Gamma_{\tilde{G}\to\overline{N}^*N+h.c.}} = 1.94\ . \tag{13}$$

4. Conclusion

We have presented the chiral Lagrangians describing the interaction of the pseudoscalar glueball with (pseudo)scalar mesons and baryons. In particular, after the recall of mesonic effective Lagrangian of Eq. (12), and the corresponding results for the mesonic decays presented in Ref. [6] (see Table I.a and I.b), we have focused our attention on a peculiar interference phenomenon taking place in the meson sector. The latter, although subdominant, should be fully taken into account in future studies. As a last step we have presented in Eq. (12) the chiral coupling of the pseudoscalar glueball with the nucleon and its chiral partner, which describes the proton fusion process $\bar{p}p \to \tilde{G}$. Finally, we have also made a prediction for the ratio of decays $\Gamma_{\tilde{G}\to\overline{N}N}/\Gamma_{\tilde{G}\to\overline{N}^{*}N+h.c.} = 1.94$, which can be experimentally checked in the future.

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